

Climate Change and Utah: The Scientific Consensus

September 2007

Executive Summary

As directed by Governor Jon Huntsman's Blue Ribbon Advisory Council on Climate Change (BRAC), this report summarizes present scientific understanding of climate change and its potential impacts on Utah and the western United States. Prepared by scientists from the University of Utah, Utah State University, Brigham Young University, and the United States Department of Agriculture, the report emphasizes the consensus view of the national and international scientific community, with discussion of confidence and uncertainty as defined by the BRAC.

There is no longer any scientific doubt that the Earth's average surface temperature is increasing and that changes in ocean temperature, ice and snow cover, and sea level are consistent with this global warming. In the past 100 years, the Earth's average surface temperature has increased by about 1.3°F, with the rate of warming accelerating in recent decades. Eleven of the last 12 years have been the warmest since 1850 (the start of reliable weather records). Cold days, cold nights, and frost have become less frequent, while heat waves have become more common. Mountain glaciers, seasonal snow cover, and the Greenland and Antarctic ice sheets are decreasing in size, global ocean temperatures have increased, and sea level has risen about 7 inches since 1900 and about 1 inch in the past decade.

Based on extensive scientific research, there is very high confidence that human-generated increases in greenhouse gas concentrations are responsible for most of the global warming observed during the past 50 years. It is very unlikely that natural climate variations alone, such as changes in the brightness of the sun or carbon dioxide emissions from volcanoes, have produced this recent warming. Carbon dioxide concentrations are now more than 35% higher than pre-industrial levels and exceed the highest natural concentrations over at least the last several hundred thousand years.

It is likely that increases in greenhouse gas concentrations are contributing to several significant climate trends that have been observed over most of the western United States during the past 50 years. These trends are: (1) a several day increase in the frost-free growing season, (2) an earlier and warmer spring, (3) earlier flower blooms and tree leaf out for many plant

species, (4) an earlier spring snowmelt and run off, and (5) a greater fraction of spring precipitation falling as rain instead of snow.

In Utah, the average temperature during the past decade was higher than observed during any comparable period of the past century and roughly 2°F higher than the 100 year average. Precipitation in our state during the 20th century was unusually high; droughts during other centuries have been more severe, prolonged, and widespread. Declines in low-elevation mountain snowpack have been observed over the past several decades in the Pacific Northwest and California. However, clear and robust long-term snowpack trends have yet to emerge in Utah's mountains.

Climate models estimate an increase in the Earth's average surface temperature of about 0.8°F over the next 20 years. For the next 100 years, the projected increase is between 3 and 7°F, depending on a range of credible estimates of future greenhouse gas emissions. These projections, combined with extensive scientific research on the climate system, indicate that continued warming will take place over the next several decades as a result of prior greenhouse gas emissions. Ongoing greenhouse gas emissions at or above current levels will further alter the Earth's climate and very likely produce global temperature, sea level, and snow and ice changes greater than those observed during the 20th century.

What does this mean for Utah? Utah is projected to warm more than the average for the entire globe and more than coastal regions of the contiguous United States. The expected consequences of this warming are fewer frost days, longer growing seasons, and more heat waves. Studies of precipitation and runoff over the past several centuries and climate model projections for the next century indicate that ongoing greenhouse gas emissions at or above current levels will likely result in a decline in Utah's mountain snowpack and the threat of severe and prolonged episodic drought in Utah is real. Preparation for the future impacts of climate variability and change on Utah requires enhanced monitoring and knowledge of Utah's climate, as well as better understanding of the impacts of weather and climate on the state's water availability, agriculture, industry, and natural resources.

1 Introduction

What do we know about climate change and its impacts on Utah and the West? As directed by Governor Jon Huntsman's Blue Ribbon Advisory Council on Climate Change (BRAC), this report summarizes our current understanding of climate change, trends and projections for the future, and possible impacts for Utah and the western United States. Prepared by a team of scientists and engineers from the University of Utah, Utah State University, Brigham Young University, and the United States Department of Agriculture (Appendix A), this understanding is consistent with the consensus view of the national and world scientific community. Scientific confidence and uncertainty are addressed throughout the report as directed by the BRAC and summarized in Appendix B.

2 The consensus view of global climate change

2.1 Evidence of a warming Earth

There is no longer any scientific doubt that the Earth's average surface temperature¹ is increasing and that changes in ocean temperature, ice and snow cover, and sea level are consistent with this global warming. In the past 100 years, the Earth's average surface temperature has increased by about 1.3°F (Fig. 1). There is very high confidence in this estimate because it is based on data that have been carefully scrutinized by the scientific community. The rate of warming has accelerated in recent decades and 11 of the last 12 years have been the warmest since 1850 (the start of reliable weather records).

Temperatures inferred from ice cores, tree rings and other sources provide a longer-term perspective on this

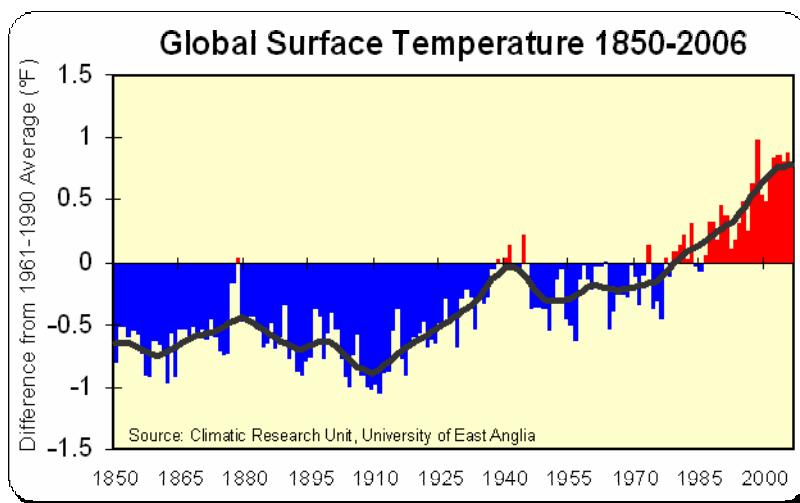


Figure 1

¹ Based on near-surface air temperature over land and sea surface temperature.

warming. Based on these reconstructions, there is very high confidence that the past few decades were warmer than any comparable period in the last 400 years. Temperature during the late-20th century appears to be higher than for any comparable period in the last 1000 years at many (but not all) locations, but because of uncertainties in temperature reconstructions beyond

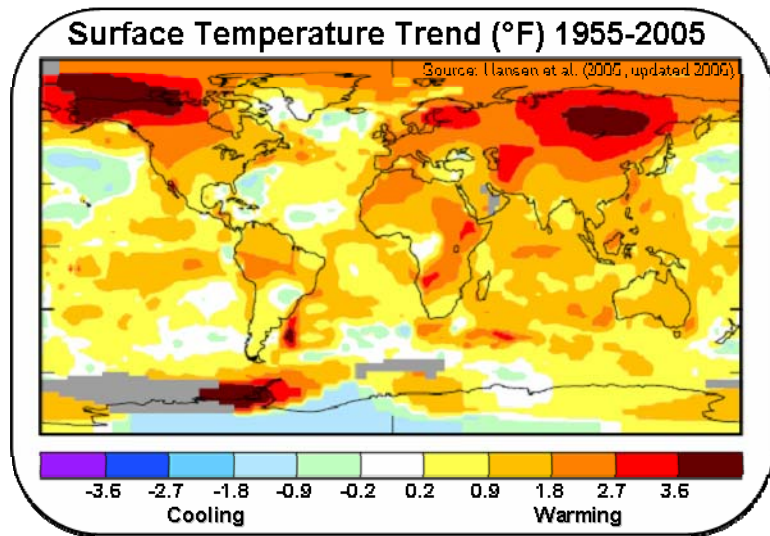


Figure 2

several hundred years before present, we are less confident about how today's average temperature compares with that prior to 1600 AD.

Temperature changes have not occurred uniformly around the globe and vary regionally (Fig. 2). Although most of the Earth has warmed, with greater warming over land than oceans, a few regions have cooled. The most rapid change is in the Arctic, which is warming twice as fast as the global average. Most of the western United States is warming faster than the global average.

Observed changes in ocean temperature, sea level, mountain glaciers, seasonal snow cover, Arctic sea ice, and the Greenland and Antarctic ice sheets are consistent with what is expected from global warming. The sea surface and upper-layers of the ocean have warmed. Sea level has risen about 7 inches since 1900 and about 1 inch in the past decade, nearly all mountain glaciers are receding, sea ice in the Arctic is declining, and the Greenland ice sheet is shrinking.

2.2 Is recent warming natural or human caused?

Without carbon dioxide and other greenhouse gases, the atmosphere would be very cold, almost 60°F colder than presently observed. Although there are natural sources of greenhouse gases, the amount of carbon dioxide in the atmosphere (381 parts per million) is now more than 35% higher than pre-industrial levels (280 parts per million) and very likely exceeds the highest natural concentrations over at least the last several hundred thousand years (Fig. 3). The added

carbon dioxide enhances the Earth's natural greenhouse effect and comes primarily from fossil fuel burning, with forest clearing playing a secondary role. Half of the post-industrial increase in carbon dioxide concentration has occurred since the mid 1970s.

Climate has changed dramatically during the Earth's history, sometimes abruptly. Changes in the Earth's tilt and distance from the sun, the

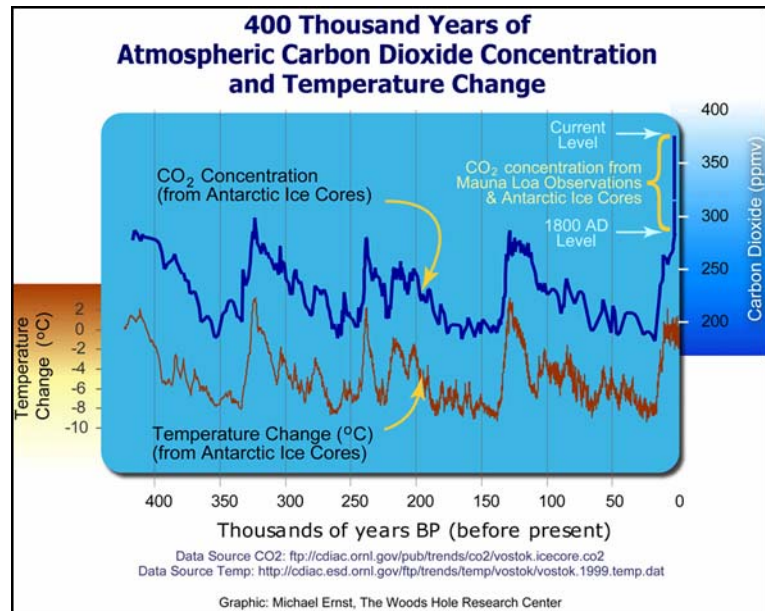


Figure 3

brightness of the sun, and volcanic eruptions are known to affect climate. Air bubbles in Antarctic ice cores provide estimates of temperature and carbon dioxide in the distant past. Temperature and carbon dioxide levels show consistent large swings between 180 and 300 parts per million over the past several hundred thousand years with low carbon dioxide during cool periods (ice ages) and high carbon dioxide during warm periods (Fig. 3). Although ice ages and the intervening warm periods are caused by gradual changes in the Earth's tilt and distance from the sun, temperature can change more abruptly due to a complicated interplay between greenhouse gases and temperature. These "feedbacks" in the climate system are not completely understood and remain an important scientific issue to resolve.

Humans affect the climate system through the production of particulate pollution, changes to the land surface, and greenhouse gas emissions. Based on extensive scientific research, there is very high confidence that human-generated increases in greenhouse gas concentrations are responsible for most of the global warming observed during the past 50 years. It is very unlikely that natural climate variations alone, such as changes in the brightness of the sun or carbon dioxide emissions from volcanoes, have produced this recent warming. Further, the Earth's climate is just beginning to respond to the rapid rise in greenhouse gas concentrations evident in Fig. 3, as discussed in section 4.

2.3 Other recent climate trends

2.3.1 Droughts and rainfall

Although estimating precipitation around the globe is difficult, observations do reveal regional changes in the distribution, intensity, and amount of precipitation. The peripheries of the deserts of North Africa have become increasingly arid during the last 100 years and drought has become more intense, widespread, and persistent in many regions since 1970. On the other hand, the frequency of heavy precipitation has increased. For example, over the contiguous United States, the average precipitation has increased by just over 10%, with over half of this increase produced by the most extreme heavy precipitation events. Although it may seem contradictory that droughts are becoming more prevalent in many regions while episodes of heavy precipitation are generally increasing, such changes are consistent with our understanding of how global warming influences the regional distribution and intensity of precipitation.

2.3.2 Sea level rise

Mean sea level rose almost 7 inches in the 20th century and about 1 inch in the past decade (Fig. 4). Expansion of the water as ocean temperature increases is the leading contributor to sea level rise with additional contributions from melting glaciers, ice caps, and ice sheets. The melting of sea ice does not appreciably influence sea level.

2.3.3 Glaciers, ice caps and sheets, and sea ice

Mountain glaciers, ice caps, and the Greenland ice sheet are shrinking and are responsible for 35-40% of the recent (1993-2003) sea level rise. The thickness and coverage of Arctic sea ice is also declining (Fig. 5), as is the extent of snow cover in the winter.

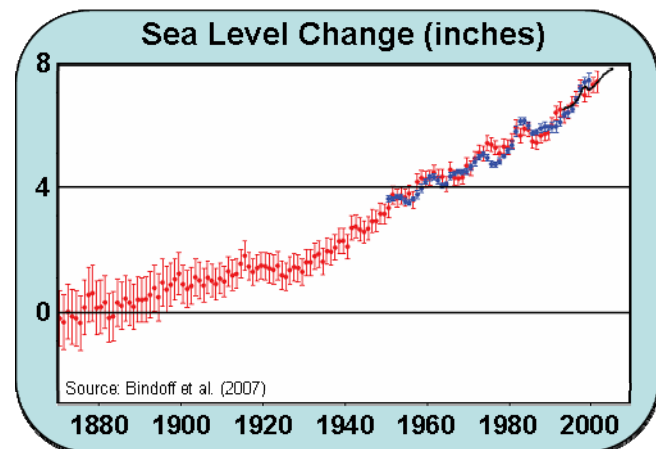


Figure 4

The large Greenland ice sheet is particularly vulnerable to warming. If fully melted, it contains enough ice to raise sea level by 22 feet. (About 130,000 years ago when the climate was warmer than it is now, the Greenland ice sheet was much smaller

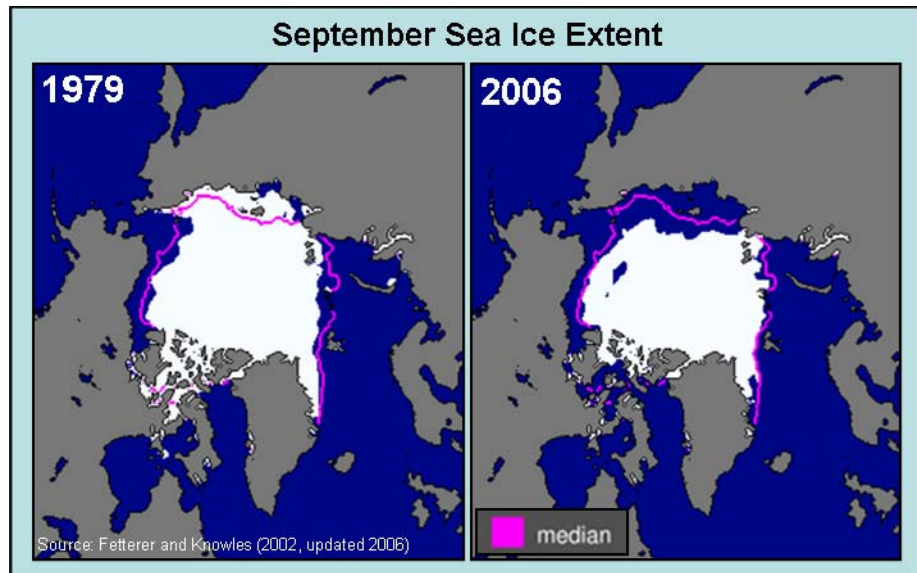


Figure 5

and sea level was at least 10 feet higher than today). From 2003-2005, the loss of ice from the Greenland ice sheet was roughly equivalent to the amount of water that flows through the Colorado River over a 12 year period.

Antarctica has the largest floating ice shelves in the world, one of which is nearly the size Utah and is 1000 feet thick. The disintegration and melting of floating ice shelves does not contribute appreciably to sea level rise. The floating ice sheets are maintained, however, by glaciers that flow seaward from the higher elevation continental regions. The loss of the floating ice shelves can accelerate the flow of continental ice into the ocean, which does raise sea level. In 2000, the 10,000 year old, 700 foot thick Larsen 'B' Ice Shelf collapsed, contributing to accelerated ice flow from land to ocean. A smaller ice shelf collapse has also been observed in the Arctic. Further ice shelf breakups will increase sea level. Our understanding of the mechanisms that lead to ice shelf collapse is incomplete, however, so the future of ice sheets in a warming world is presently uncertain.

Satellite observations show that the area of the Arctic ice cap has decreased (about 7.5% per decade during the past 25 summers). The average thickness of Arctic sea ice has also declined.

2.3.4 Hurricanes and tropical cyclones

Hurricane is the common name for a *tropical cyclone* in the western hemisphere. Elsewhere they are known as *typhoons* or just cyclones. The active 2005 hurricane season underscores the vulnerability of the southern and eastern sections of the United States to these weather events.

Knowledge of tropical cyclone trends is based on long-term datasets that are imperfect, particularly before the widespread use of satellite imagery in the 1970s. With consideration of the limitations of the existing datasets, we summarize the current understanding as follows:

- There has been little or no long-term trend in the average *number* of tropical cyclones that occur across the entire globe each year.
- It is likely that *intense hurricane activity* has increased over the Atlantic Ocean since 1970.
- Although global warming may affect the frequency of intense hurricanes, direct attribution for the creation of individual hurricanes to global warming is not possible.

There is no doubt that the ever-growing concentration of population and development in vulnerable coastal regions is the primary driver of the increasing financial losses produced by hurricanes. If present development trends continue in these regions, we can expect even larger human and economic losses from hurricane disasters.

2.3.5 Species and habitats

Plants and animals respond not only to changes in climate, but also to changes in their habitat caused by fires, insect outbreaks, invasion of non-native species, human land use patterns, etc. While it is a challenge to attribute plant and animal responses solely to a change in climate in the presence of these other factors, about 90% of documented changes to plant and animal species across the globe are consistent with recent climate change.

It is very likely that earlier warming in the spring is strongly affecting plants, animals, and insects. Events that are occurring earlier in the spring include the greening of grasses and

trees, flowering of plants, migration of birds and insects, and laying of eggs. For example, the average date of first bloom for lilacs and honeysuckles has advanced more than a week over the last 40 years in the western United States. Recent climate change has led to mismatches between bird migration timing and their insect food sources, between insects and plant food sources, and between plants and the birds and insects that help them reproduce. For example, marmots at one location in Colorado are now emerging from hibernation before the emergence of plants that they depend on for food.

There is very high confidence that the ranges of some plants and animals have moved towards the poles or towards higher elevations. Treeline in the Canadian Rockies has advanced upward and the distribution of high mountain plants in the Alps has shifted to higher elevations. Butterfly ranges have expanded northward all over Europe. The range of shrubs in northern Alaska, Canada, and Russia has moved northward into tundra regions. Hummingbirds that formerly wintered in Mexico are now found regularly in the Gulf Coast states.

3 Climate Change in the Western United States and Utah

It is likely that increases in greenhouse gas concentrations are contributing to several significant climate trends that have been observed over most of the western United States during the past 50 years. These trends are: (1) a several day increase in the frost-free growing season, (2) an earlier and warmer spring, (3) earlier flower blooms and tree leaf out for many plant species, (4) an earlier spring snowmelt and run off, and (5) a greater fraction of spring precipitation falling as rain instead of snow. In Utah, the average temperature during the past decade was higher than that observed during any comparable period of the past century and roughly 2°F higher than the 100 year average (Fig. 6).

Most of Utah's water resources originate in

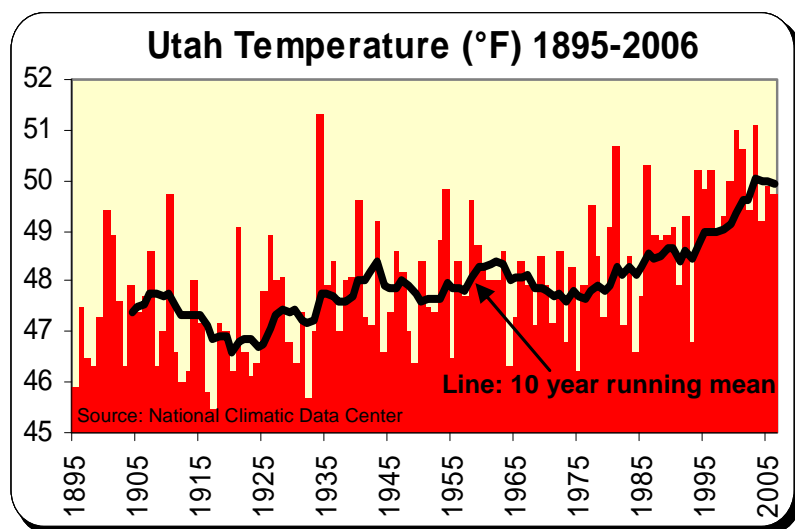


Figure 6

mountainous areas above 6500 feet in elevation, which cover about 19% of the state. The primary source of this water is snowpack.

Snow accumulates in these mountainous areas during winter and then melts in spring and early summer releasing months of stored precipitation in typically 4

to 8 weeks time. The release of this stored water over a short time generates the majority of streamflow across the state.

Precipitation fluctuates dramatically in Utah from year to year, complicating the identification of long term trends. Using geologic records and tree rings, however, scientists have produced estimates of river flow and precipitation in the Colorado River Basin dating back several hundred years. These estimates show that sustained droughts are a defining feature of the upper Colorado River Basin, which has experienced far more prolonged and severe drought than observed during the comparatively wet 20th century. Persistent drought occurred in the late 16th century, with river flows during this period much lower than for any period in the 20th century. The drought of 1999-2004 was a severe event, but there have been even longer and more severe droughts in the past.

Declines in low-elevation mountain snowpack have been observed over the past several decades in the Pacific Northwest and California. However, in Utah, careful analysis of long-term (80 year) snow surveys shows no evidence for a clear long-term trend in mountain snowpack. In addition, recent temperature increases in the state appear to have had little impact on snowpack in the high mountains of the Intermountain West. Streamflows in Utah and the Intermountain West also do not show clear trends over the past 50 years.

The level of the Great Salt Lake reflects to a large degree the total precipitation received over much of northern Utah. Several wet years led to high lake levels in the mid 1980's, while

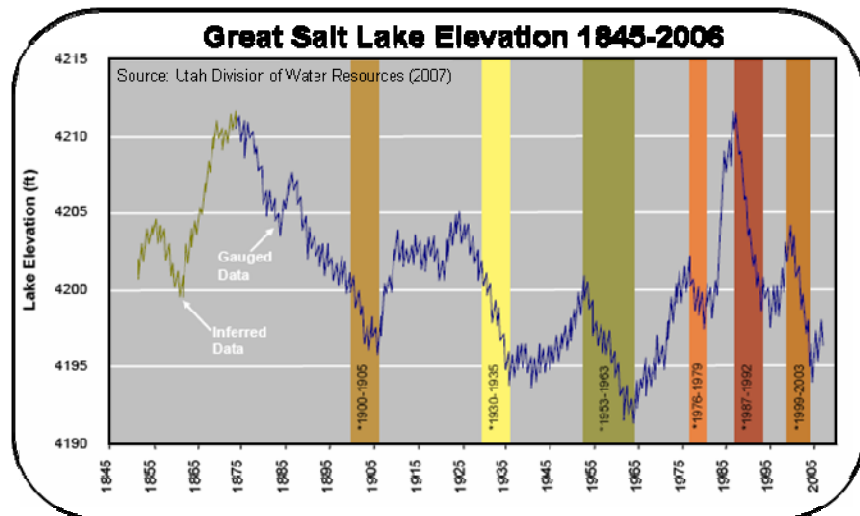


Figure 7. Great Salt Lake elevation with drought periods indicated by colored bars.

the 1999-2004 drought led to falling lake levels (Fig. 7). The causes for these swings in basin precipitation are not completely understood, and, at this time, there is no clear linkage between recent global warming and precipitation within the basin of the Great Salt Lake.

4 Projections for future global climate change

4.1 Overview of climate models

The Earth's climate is too complex to assess and predict by physical reasoning or laboratory experiments alone (Fig. 8). Therefore, scientists use well-established physical principles to build sophisticated computer codes, or climate models, which simulate the past, present, and future climate. These models can be used, for example, to understand how the build-up of greenhouse gases or a volcanic eruption might modify temperature, rainfall, snow cover, winds, soil moisture, sea ice, and ocean circulations.

4.2 Strengths and limitations of climate models

Unlike weather forecast models, climate models are not intended to forecast what will happen on a particular day in the future. Rather, climate models are designed to estimate the average conditions over many years. There is considerable confidence that today's climate models provide credible estimates of future climate for the Earth as a whole and for large regions like entire continents. This confidence is derived from the ability of climate models to reproduce many observed features of recent and past climate. In addition, confidence is improved by

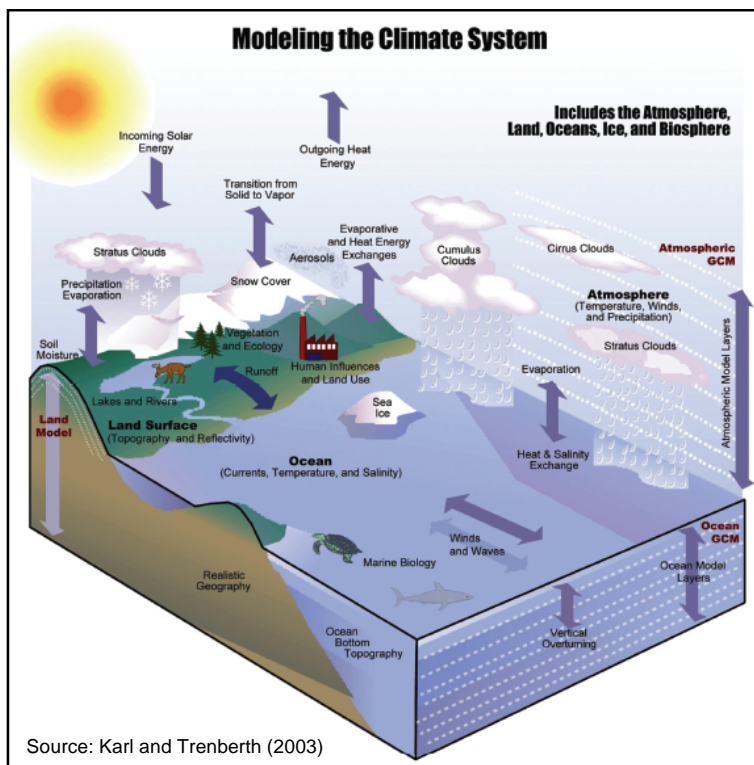


Figure 8

evaluating the results from a number of different models.

Since climate models are simplified versions of the Earth's climate system, they cannot capture its full complexity, especially in mountainous regions such as Utah. For example, current climate models divide the globe into a mosaic of squares that are too big to directly

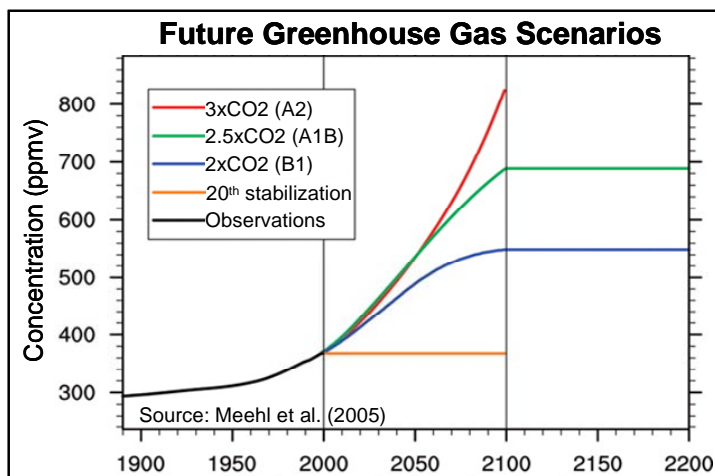


Figure 9

simulate the impact of individual mountain ranges in Utah. For this and other reasons, climate model projections become less reliable for particular regions, states, or locations.

4.3 *Future greenhouse gas scenarios*

Estimates of future greenhouse gas concentrations, called scenarios, are used to produce different projections for future climate (Fig. 9). Three commonly used scenarios are:

- 2xCO₂, which projects that greenhouse gas concentrations stabilize by the end of the 21st century at double their pre-industrial levels.
- 2.5xCO₂, which projects that greenhouse gas concentrations reach 2.5 times their pre-industrial levels by the end of the century.
- 3xCO₂, which projects that greenhouse gas concentrations reach three times their pre-industrial levels by the end of the century².

A fourth hypothetical scenario, 20th century stabilization, assumes greenhouse gas concentrations remain at year 2000 levels. Since greenhouse gas concentrations are already above year 2000 levels and climbing, this scenario illustrates the anticipated response of the Earth's climate to emissions that have already occurred.

² The Intergovernmental Panel on Climate Change (IPCC) refers to the 2xCO₂, 2.5xCO₂ and 3xCO₂ scenarios as B1, A1B, and A2, respectively.

4.4 Projected changes

Climate model projections, when combined with other research on the climate system, indicate that *(1) continued climate change will take place over the next several decades as a result of prior greenhouse gas emissions and (2) ongoing greenhouse gas emissions at or above current levels will very likely produce global temperature, sea level, and snow and ice changes greater than those observed during the 20th century.*

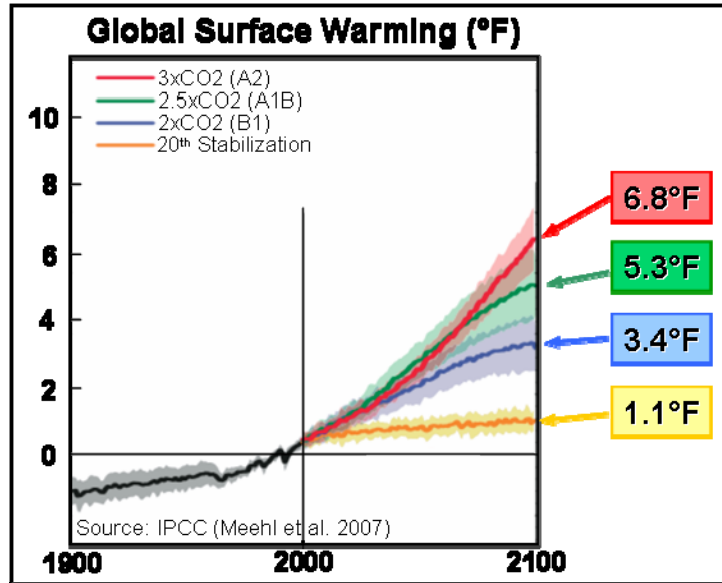


Figure 10

4.4.1 Temperature

Climate models project an increase in the Earth's average surface temperature of about 0.8°F over the next 20 years. This projected warming is largely independent of future emission scenarios (2xCO₂, 2.5xCO₂, or 3xCO₂) and is primarily the result of prior and current greenhouse gas emissions. By 2100, climate models project an increase in global mean surface temperature of between 3 and 7°F, with greater warming for larger projected increases in carbon dioxide (Fig. 10). For each scenario, the projected warming differs between climate models, but these differences are small compared to the size of the overall warming. Because the Earth's climate takes time to respond, warming (as well as ice melt and sea level rise) continues for centuries after greenhouse gas concentrations stabilize, as illustrated by the 1.1°F of warming projected by the hypothetical 20th century stabilization scenario by 2100.

Some general statements about the expected spatial distribution of the warming (Fig. 11) are:

- Areas that have experienced the most warming during the past few decades will experience the most warming in the future;

- Warming will be greater over land than over oceans;
- Warming will be greater over the interiors of the continents than at the coasts;
- Warming will be greatest in the Arctic;
- Warming will be larger in winter than in summer.

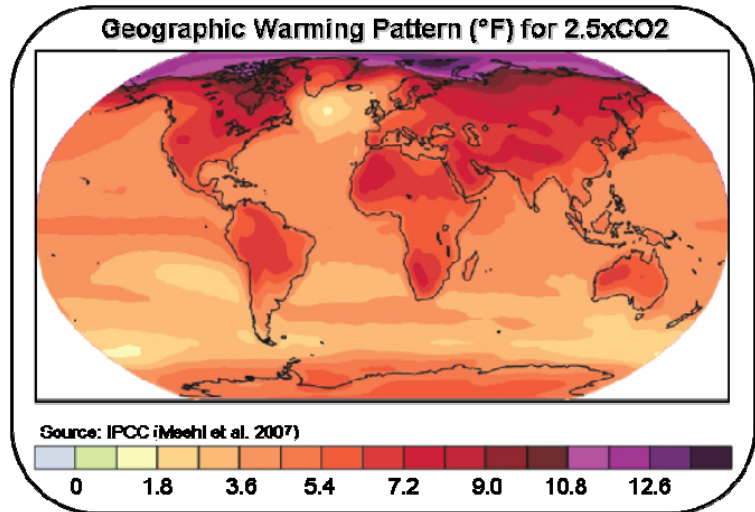


Figure 11. Projected surface temperature change from the late 20th century to the late 21st century.

Utah is projected to warm more than the average for the entire globe and more than coastal regions of the contiguous United States. The expected consequences of this warming are fewer frost days, longer growing seasons, and more heat waves. For Utah, the projected change in annual mean temperature under the 2.5xCO₂ scenario by the end of this century is about 8°F, which is comparable to the present difference in annual mean temperature between Park City (44°F) and Salt Lake City (52°F).

4.4.2 Rainfall, storms, and

Weather

In contrast to temperature, which is projected to increase everywhere, changes in precipitation vary regionally and there is greater uncertainty about the model projections. The climate models project more precipitation

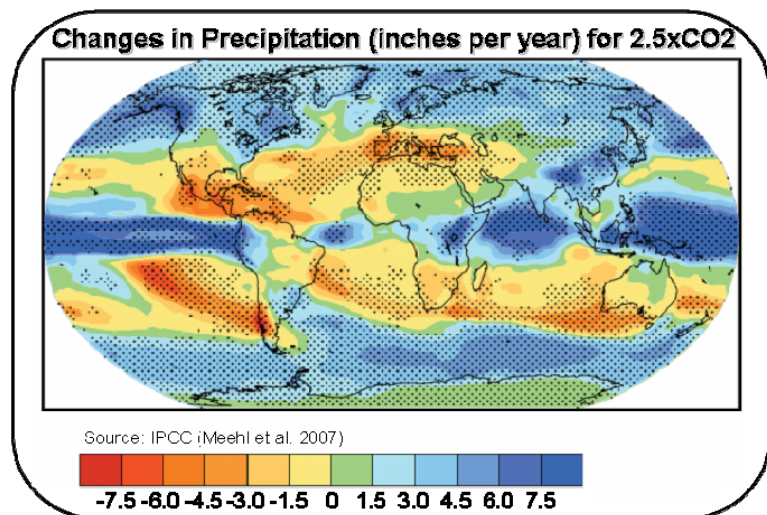


Figure 12. Projected change in precipitation from the late 20th century to the late 21st century.

for the mid and high latitudes and drying across most of the subtropics including southwest North America, Mexico, North Africa, and southern Europe. There is a general tendency among the models for more frequent heavy precipitation events, separated by longer dry spells, especially in Utah and the western United States.

4.4.3 Sea level

It is likely that sea level will continue to rise at rates at or above those observed in the 20th century. There are two major contributors to sea level rise. The first is that water expands as it warms, called thermal expansion. The second is water flowing into the oceans from melting glaciers, ice caps, and ice sheets.

Current climate models project a sea level rise due only to thermal expansion of 7 to 23 inches by the end of the 21st century, depending on which emissions scenario and model is considered. Any shrinking of the Antarctic and Greenland ice sheets, which is not included in current climate model projections, will lead to additional sea level rise. Due to the slow response of the Earth's climate, sea level rise will continue for many centuries after greenhouse gas concentrations are stabilized.

4.5 ***Projected impacts***

4.5.1 Projections for human health and diseases

Negative health effects associated with climate change are expected to outweigh positive ones, particularly for those in developing countries. The consequences for society will be strongly regional, with people in poor regions expected to be most vulnerable as they have less capacity to adapt and depend generally on locally produced food and water. These consequences include increases in deaths, disease, and injuries due to heat waves, extreme weather events, malnutrition (caused by crop failure), intestinal disease, and allergy-causing pollen. Cold exposure deaths are expected to decline. Climate change will also alter the transmission of infectious diseases such as cholera, malaria, and bubonic plague. The production of near-surface ozone and associated cardio-respiratory diseases is expected to increase.

4.5.2 Projections for agriculture and food production

At mid- to high latitudes where increased precipitation and a longer growing season are expected, crop productivity will likely increase slightly for local temperature increases of 2-5°F (depending on the crop), above which productivity will decline in some regions. At lower latitudes, crop productivity is projected to decrease even for small temperature increases. Where susceptible, increases in the frequency of droughts will affect agricultural production. Changes in the distribution and population of insects and animals will likely have positive and negative effects on crops through changes in the magnitude, location, and timing of insect damage and pollination.

4.5.3 Projections for biodiversity

The biodiversity of plants, animals and other organisms on the earth is decreasing dramatically, representing the sixth major extinction event in the history of life. While climate change is a factor in decreasing biodiversity, other modifications of the environment are primarily responsible, including human land use, agricultural and hunting/fishing practices, pollution, and introduction of non-native species.

Estimates of the influence of climate change on biodiversity suggest that 20-30% of all known plant and animal species will be more vulnerable to extinction during the next century. Climate change will probably not influence biodiversity by itself; instead, pressures from land use change or the other factors listed above will be increased by climate change. Depending on the projection scenario, more than half of plant species in Europe could be vulnerable or threatened by the late 21st century. Twelve percent of all known bird species are estimated to be threatened currently with extinction, and this is expected to be larger with global warming. Species whose home range is restricted by cold temperatures at high latitudes or altitudes, or whose habitat is limited by land use change, are at higher risk.

4.6 *Feedbacks, tipping points, and the threat of catastrophic climate change*

Climate feedbacks are important for future climate change because the warming produced by increased greenhouse gas concentrations can be amplified (or reduced) by other indirect effects. For example, as greenhouse gas warming melts arctic sea ice, sunlight that was

previously reflected back to space by the ice is now absorbed by the dark ocean. This is a “positive feedback” that results in additional warming. These feedbacks are very important, since they can increase or reduce the initial temperature change by large amounts. Uncertainties in feedbacks are partly responsible for the fact that different climate models produce different amounts of warming in the 21st century.

“Tipping point” has been used to describe the crossing of a threshold greenhouse gas concentration beyond which we cannot avoid catastrophic climate change. What constitutes catastrophic climate change is somewhat arbitrary, but the inability to maintain sea level near current levels is a common definition. For example, as greenhouse gas concentrations increase, a threshold may be reached whereby we are committed to a slow but major rise in sea level. It is likely that tipping points exist in the Earth's climate, as indicated by dramatic climate shifts over the past several hundred thousand years (e.g., Fig. 3). At the current level of scientific understanding, it is unclear where these tipping points are or if they have already been passed. Identifying these tipping points represents an important scientific problem since catastrophic, abrupt climate change represents the greatest potential risk from rising greenhouse gas concentrations.

5 Climate change and impacts on Utah

Climate change is expected to vary regionally, but estimates of future regional climate change and its impacts on specific states are less certain than global estimates. It is with this in mind that the following discussion considers the potential impacts of projected future climate change on Utah and the Intermountain West.

5.1 Impacts on snowpack, water supply, and drought potential

Ongoing greenhouse gas emissions at or above current levels will likely result in a decline in Utah's mountain snowpack and associated changes to spring runoff. Year-to-year variations in snowfall will continue to dominate mountain snowpack, streamflow, and water supply during the next couple of decades. As temperature increases through the century, it is likely that a greater fraction of precipitation will fall as rain instead of snow, the length of the

snow accumulation season will decrease, and snowpack loss due to evaporation will increase. Trends that are likely to emerge as the climate warms during the 21st century include:

- A reduction in natural snowpack and snowfall in the early and late winter for the winter recreation industry, particularly in lower-to-mid elevation mountain areas (trends in high elevation areas are unclear).
- An earlier and less intense average spring runoff for reservoir recharge.
- Increased demand for agricultural and residential irrigation due to more rapid drying of soils.
- Warming of lakes and rivers with associated changes on aquatic life, including increased algal abundance and upstream shifts of fish habitat.

Future water supplies are strongly dependent on long-term trends in precipitation. If average precipitation remains similar to that of the 20th century, the changes noted above will result in a declining water supply. This decline will be exacerbated if the region becomes more arid. An increase in precipitation is required to offset the changes noted above. Current climate models project a decline in summer precipitation across all of Utah. During the winter, projections indicate a decrease in precipitation over the southwest United States and an increase in the northwest. Utah is located in the transition zone between these regimes where there is low confidence in future precipitation trends. Although a shift to a wetter climate cannot be ruled out, *it is more likely than not that water supplies in Utah and the Colorado River Basin will decline during the 21st century.* In addition, since precipitation will continue to fluctuate from year to year, *the threat of severe and prolonged episodic drought is real and ongoing.*

5.2 Impacts on the Great Salt Lake

Year-to-year variations in mountain snowfall will continue to drive runoff in the Great Salt Lake Basin and the level of the Lake (temperature and evaporation of lake water plays a secondary role). There is limited ability to predict these variations and associated changes in lake level under current climate conditions. *As temperature increases, however, expected declines in mountain snowpack will likely lead to lower average lake levels and increased*

average salinity unless average winter precipitation increases. These changes will affect wetland habitat and wildlife, as well as commercial and recreation activities that rely on the Lake. How soon these changes will occur remains unclear.

5.3 Impacts on agriculture

Agriculture in Utah produces over \$1 billion in cash receipts annually, with livestock and related products accounting for about 80% of this figure. Agricultural irrigation covers about 1.5 million acres and is the primary use of developed water in the state. Future agricultural productivity is affected not only by climate change, but also factors such as agricultural research and practices, expansion of urban development into farmland, etc. Based solely on climate change, per-acre crop yields in Utah will likely increase on irrigated fields provided (1) water remains available for irrigation and (2) temperatures do not increase beyond crop tolerance levels. Pasture yields and livestock forage will likely decline on non-irrigated fields. Climate change may also have indirect effects on crop yields through changes in the distribution and population of insects and animals, which affects pollination and crop damage.

5.4 Impacts on human health

Impacts on human health are difficult to discern because they are also dependent on technological adaptation and other non-climatic factors. For example, human mortality during heat waves is strongly influenced by the availability of residential air conditioning. If non-climatic factors do not change, expected impacts on human health include:

- Increased heat-related illness and mortality.
- Decreased hypothermia related deaths.
- Increased ground-level ozone concentrations and associated cardio-respiratory diseases.
- Changes in the distribution and morbidity of diseases that are transmitted by insects and animals.

5.5 Impacts on forests, wildlands, and wildfire

Forests and wildlands are adapted to recent climatic conditions and variability, but the rate of temperature change expected during the next century will greatly exceed that produced naturally over the past several thousand years. Forests, wildlands, and wildfires will also be affected by management practices, and other factors such as land-use change. In isolation, future climate change is likely to contribute to:

- Drier conditions and increased wildfire intensity.
- More insect outbreaks and reduced forest health.
- Movement of tree and plant species ranges to higher elevations.

5.6 Impacts on soils

Because of increasing temperature, soils are expected to dry more rapidly, which will likely increase soil vulnerability to wind erosion. This will increase dust transport during high wind events, particularly from salt flats and dry lake beds such as Sevier Lake. Dust deposited on mountain snowpack also accelerates spring snowmelt.

6 Improving assessments of climate change impacts

Preparation for the future impacts of climate variability and change on Utah requires improved monitoring and knowledge of Utah's climate, as well as better understanding of the impacts of weather and climate on the state's water availability, agriculture, industry, and wildlife. While considerable progress has been made over the past decade to understand and project the consequences of increasing greenhouse gas concentrations globally, much work remains to improve understanding of the consequences for Utah. Advances in our understanding and predictive abilities will enable the most effective adaptation to and mitigation of future climate change for Utah's citizens, economy, and natural resources.

For More Information

Climate Change 2007: The Physical Science Basis

Summary for Policymakers: http://www.ipcc.ch/WG1_SPM_17Apr07.pdf

Frequently Asked Questions: http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_FAQs.pdf

Full Report: <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>

Climate Change 2007: Impacts, Adaptation, and Vulnerability

Summary for Policymakers: <http://www.ipcc.ch/SPM13apr07.pdf>

Full Report: <http://www.gtp89.dial.pipex.com/chpt.htm>

Drought in Utah: Learning from the Past – Preparing for the Future

Full Report: <http://www.water.utah.gov/DroughtReport/binder2A.pdf>

Appendix A: Team Members

Dr. Jim Steenburgh, Team Leader
Professor and Chair
Department of Meteorology
University of Utah
135 South 1460 East Room 819
Salt Lake City, UT 84112-0110
Jim.Steenburgh@utah.edu
801-581-8727

Dr. David Bowling
Assistant Professor
Department of Biology
University of Utah
Aline Wilmot Skaggs Building Room 440
257 South 1400 East
Salt Lake City, UT 84112
bowling@biology.utah.edu
801-581-2130

Dr. Tim Garrett
Assistant Professor
Department of Meteorology
University of Utah
135 South 1460 East Room 819
Salt Lake City, UT 84112-0110
tim.garrett@utah.edu
801-581-5768

Dr. Rob Gillies
Director/State Climatologist
Utah Climate Center
Utah State University
4825 Old Main Hill
Logan, UT 84322-4825
rgillies@gis.usu.edu
435-797-2190

Dr. John Horel
Professor
Department of Meteorology
University of Utah
135 South 1460 East Room 819
Salt Lake City, UT 84112-0110
john.horel@utah.edu
801-581-7091

Randy Julander
Snow Survey Supervisor
Natural Resources Conservation Service
245 North Jimmy Doolittle Road
Salt Lake City, UT 84116
Randy.Julander@ut.usda.gov
801-524-5213

Dr. David Long
Professor
Department of Electrical and
Computer Engineering
Director, BYU Center for Remote Sensing
459 Clyde Building
Brigham Young University
Provo, UT 84602
long@byu.edu
801-422-4383

Dr. Thomas Reichler
Assistant Professor
Department of Meteorology
University of Utah
135 South 1460 East Room 819
Salt Lake City, UT 84112-0110
thomas.reichler@utah.edu
801-585-0040

Appendix B: Scientific Confidence and Uncertainty

As directed by the BRAC this report addresses issues of confidence and uncertainty. The report follows the guidelines used by the Intergovernmental Panel on Climate Change (IPCC) for their Four Assessment Report (available in full at <http://www.ipcc.ch/activity/uncertaintyguidancenote.pdf>). Both level of confidence and likelihood based on quantitative analysis or expert judgment are used and reflect definitions as outlined in the tables below.

Table 1. Levels of confidence

| Terminology | Degree of confidence in being correct |
|----------------------|--|
| Very high confidence | At least 9 out of 10 |
| High confidence | About 8 out of 10 |
| Medium confidence | About 5 out of 10 |
| Low confidence | About 2 out of 10 |
| Very low confidence | Less than 1 out of 10 |

Table 2. Likelihood

| Terminology | Likelihood of the occurrence/outcome |
|------------------------|---|
| Virtually certain | Greater than 99% |
| Very likely | Greater than 90% |
| Likely | Greater than 66% |
| About as likely as not | 33 to 66% |
| Very unlikely | Less than 10% |
| Exceptionally unlikely | Less than 1% |

References

Executive Summary

- Bindoff, N. L., and coauthors, 2007: Observations: Oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch05.pdf].
- Cayan, D. R., and coauthors, 2001: Changes in the onset of spring in the western United States. *Bull. Amer. Meteor. Soc.*, **82**, 399–415.
- Christensen, J. H., and coauthors, 2007: Regional Climate Projections. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch11.pdf].
- Christensen, N., and D. P. Lettenmaier, 2006: A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. *Hydrol. Earth Syst. Sci. Discuss.*, **3**, 3727–3770.
- Cowles, M. K. and coauthors, 2002, Combining snow water equivalent data from multiple sources to estimate spatio-temporal trends and compare measurement systems. *J. Ag., Bio., and Env. Stat.*, **7**, 536–557.
- Hegerl, G. C., and coauthors, 2007: Understanding and attributing climate change. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch06.pdf].
- Jansen, E., and coauthors, 2007: Paleoclimate. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch09.pdf].
- Karl, T. R., and K. E. Trenberth, 2003: Modern global climate change. *Science*, **302**, 1719–1723.
- Knowles, N., and coauthors, 2006: Trends in snowfall versus rainfall in the western United States. *J. Climate*, **19**, 4545–4559.
- Lemke, P., and coauthors, 2007: Observations: Changes in snow, ice, and frozen ground. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press,

- Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch04.pdf].
- Meehl, G. A., and coauthors, 2007: Global Climate Projections. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch10.pdf].
- Mote, P. W., and coauthors, 2005: Declining mountain snowpack in western North America, *Bull. Amer. Meteor. Soc.*, **86**, 39-49.
- NRC, 2006: *Surface Temperature Reconstructions for the Last 2,000 Years*. The National Academies Press, Washington, D.C. [Available at http://www.nap.edu/catalog.php?record_id=11676].
- Regonda, S. K., and coauthors, 2005: Seasonal cycle shifts in hydroclimatology over the western United States. *J. of Climate*, **18**, 372-384.
- Stewart, I. T., and coauthors, 2005: Changes toward earlier streamflow timing across western North America. *J. Climate*, **18**, 1136-1155.
- Trenberth, K.A., and coauthors, 2007: Observations: Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch03.pdf].
- Utah Division of Water Resources, 2007: Drought in Utah: Learning from the Past – Preparing for the Future. *Utah State Water Plan*, 124 pp. [Available at <http://www.water.utah.gov/DroughtReport/binder2A.pdf>].
- Woodhouse, C. A., 2004: A paleo perspective on hydroclimatic variability in the western United States. *Aquatic Sciences*, **66**, 346-356.

Section 2.1

- Bindoff, N. L., and coauthors, 2007: Observations: Oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch05.pdf].
- Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2005, updated 2006: *Global Temperature Trends: 2005 Summation*. New York, NY. NASA Goddard Institute for Space Studies. Digital media.
- Jansen, E., and coauthors, 2007: Paleoclimate. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and

H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch09.pdf].

Lemke, P., and coauthors, 2007: Observations: Changes in snow, ice, and frozen ground. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch04.pdf].

NRC, 2006: *Surface Temperature Reconstructions for the Last 2,000 Years*. The National Academies Press, Washington, D.C. [Available at http://www.nap.edu/catalog.php?record_id=11676].

Trenberth, K.A., and coauthors, 2007: Observations: Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch03.pdf].

Section 2.2

Forster, P., and coauthors, 2007: Observations: Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch02.pdf].

Hegerl, G. C., and coauthors, 2007: Understanding and attributing climate change. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch06.pdf].

Jansen, E., and coauthors, 2007: Paleoclimate. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch09.pdf].

Section 2.3.1

Karl, T. R., and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.*, **79**, 231-241.

Trenberth, K.A., and coauthors, 2007: Observations: Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University

Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch03.pdf].

Section 2.3.2

Bindoff, N. L., and coauthors, 2007: Observations: Oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch05.pdf].

Section 2.3.3

Bindoff, N. L., and coauthors, 2007: Observations: Oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch05.pdf].

Cuffey, K. M., and S. J. Marshall, 2000: Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. *Nature*, **404**, 591-594.

Fetterer, F., and K. Knowles, 2002, updated 2006: *Sea ice index*. Boulder, CO. National Snow and Ice Data Center. Digital media.

Lemke, P., and coauthors, 2007: Observations: Changes in snow, ice, and frozen ground. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch04.pdf].

Luthcke, S. B., and coauthors, 2006: Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science*, **314**, 1286-1289.

Scambos, T. A., and coauthors, 2004: Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophys. Res. Lett.* **31**, L18402, doi:10.1029/2004GL020670.

Section 2.3.4

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686-688.

Love, G.B., 2006: Statement on tropical cyclones and climate change. WMO/CAS Tropical Meteorology Research Program, Steering Committee for Project TC-2: Scientific Assessment

- of Climate Change Effects on Tropical Cyclones. [Available at <http://www.bom.gov.au/info/CAS-statement.pdf>].
- Pielke, Jr., R.A., and coauthors, 2007. Normalized Hurricane Damages in the United States: 1900-2005. *Natural Hazards Review*, submitted. [Available at http://sciencepolicy.colorado.edu/publications/special/nhd_paper.pdf].
- Pielke, Jr., R. A., 2007. Future Economic Damage from Tropical Cyclones: Sensitivities to Societal and Climate Changes, *Proceedings of the Philosophical Transactions of the Royal Society*. In Press. [Available at http://sciencepolicy.colorado.edu/admin/publication_files/resource-2517-2007.14.pdf.]
- Trenberth, K.A., and coauthors, 2007: Observations: Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch03.pdf].
- Webster, P.J., and coauthors, 2005: Changes in tropical cyclone number, duration and intensity in a warming environment. *Science*, **309**, 1844-1846.
- Section 2.3.5**
- Both, C., and coauthors, 2006: Climate change and population declines in a long-distance migratory bird. *Nature*, **441**, 81-83.
- Cayan, D. R., and coauthors, 2001: Changes in the onset of spring in the western United States. *Bull. Amer. Meteor. Soc.*, **82**, 399-415.
- Grabherr, G., and coauthors, 1994: Climate effects on mountain plants. *Nature*, **369**, 448.
- Harrington, R., and coauthors, 1999: Climate change and trophic interactions. *Trends in Ecology & Evolution*, **14**, 146-150.
- Hill, G. E., and coauthors, 1998: Recent change in the winter distribution of Rufous Hummingbirds. *Auk*, **115**, 240-245.
- Inouye, D. W., and coauthors, 2000: Climate change is affecting altitudinal migrants and hibernating species. *Proceedings of the National Academy of Sciences of the United States of America*, **97**, 1630-1633.
- IPCC, 2007: Climate Change 2007: Impacts, Adaptation, and Vulnerability, Summary for Policy Makers. [Available at <http://www.ipcc.ch/SPM13apr07.pdf>].
- Luckman, B., and T. Kavanagh, 2000: Impact of climate fluctuations on mountain environments in the Canadian Rockies. *Ambio*, **29**, 371-380.

Parmesan, C., and coauthors, 1999: Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature*, **399**, 579-583.

Sturm, M., and coauthors, 2001: Increasing shrub abundance in the Arctic. *Nature*, **411**, 546.

Section 3

Cayan, D. R., and coauthors, 2001: Changes in the onset of spring in the western United States. *Bull. Amer. Meteor. Soc.*, **82**, 399–415.

Hamlet, A. F., and coauthors, 2007: Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. *J. Climate*, **20**, 1468-1486.

Knowles, N., and coauthors, 2006: Trends in snowfall versus rainfall in the western United States. *J. Climate*, **19**, 4545-4559.

Mote, P. W., and coauthors, 2005: Declining mountain snowpack in western North America. *Bull. Amer. Meteor. Soc.*, **86**, 39-49.

Stewart, I. T., and coauthors, 2005: Changes toward earlier streamflow timing across western North America. *J. Climate*, **18**, 1136-1155.

Utah Division of Water Resources, 2007: Drought in Utah: Learning from the Past – Preparing for the Future. *Utah State Water Plan*, 124 pp. [Available at <http://www.water.utah.gov/DroughtReport/binder2A.pdf>].

Woodhouse, C. A., 2004: A paleo perspective on hydroclimatic variability in the western United States. *Aquatic Sciences*, **66**, 346-356.

Woodhouse, C.A. and J.J. Lukas, 2006: Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. *Climatic Change*, **78**, 293-315.

Woodhouse, C. A., and coauthors, 2006: Updated streamflow reconstructions for the upper Colorado River Basin. *Water Resources Research*, **42**, W05415, doi:10.1029/2005WR004455.

Sections 4.1-4.4

Karl, T. R. and K. E. Trenberth, 2003: Modern global climate change. *Science*, **302**, 1719-1723.

Meehl, G. A., and coauthors, 2005: How much more global warming and sea level rise? *Science*, **307**, 1769-1772.

Meehl, G. A., and coauthors, 2007: Global Climate Projections. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch10.pdf].

Section 4.5.1

Beggs, P. J., 2004: Impacts of climate change on aeroallergens: past and future. *Clinical and Experimental Allergy*, **34**, 1507-1513.

Filleul, L., and coauthors, 2006: The relation between temperature, ozone, and mortality in nine French cities during the heat wave of 2003. *Environmental Health Perspectives*, **114**, 1344-1347.

IPCC, 2007: Climate Change 2007: Impacts, Adaptation, and Vulnerability, Summary for Policy Makers. [Available at <http://www.ipcc.ch/SPM13apr07.pdf>].

Pascual, M., and coauthors, 2006: Malaria resurgence in the East African highlands: Temperature trends revisited. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 5829-5834.

Rodo, X., and coauthors, 2002: ENSO and cholera: A nonstationary link related to climate change? *Proceedings of the National Academy of Sciences of the United States of America*, **99**, 12901-12906.

Stenseth, N. C., and coauthors, 2006: Plague dynamics are driven by climate variation. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 13110-13115.

Section 4.5.2

IPCC, 2007: Climate Change 2007: Impacts, Adaptation, and Vulnerability, Summary for Policy Makers. [Available at <http://www.ipcc.ch/SPM13apr07.pdf>].

Section 4.5.3

Chapin, F. S., and coauthors, 2000: Consequences of changing biodiversity. *Nature*, **405**, 234-242.

IPCC, 2007: Climate Change 2007: Impacts, Adaptation, and Vulnerability, Summary for Policy Makers. [Available at <http://www.ipcc.ch/SPM13apr07.pdf>].

Pimm, S., and coauthors, 2006: Human impacts on the rates of recent, present, and future bird extinctions. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 10941-10946.

Thomas, C. D., and coauthors, 2004. Extinction risk from climate change. *Nature*, **427**, 145-148.

Thuiller, W., and coauthors, 2005. Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **102**, 8245-8250.

Section 4.6

Hansen, J., and coauthors, 2007: Dangerous human-made interference with climate: A GISS modelE study. *Atmospheric Chemistry and Physics*, **7**, 2287-2312

Schellnhuber, and coeditors, 2006: Avoiding Dangerous Climate Change, Cambridge Univ. Press, 392 pp. [Available online at <http://www.defra.gov.uk/environment/climatechange/research/dangerous-cc/pdf/avoid-dangercc.pdf>].

Schneider, S. H., 2004: Abrupt non-linear climate change, irreversibility, and surprise. *Global Environmental Change*, **14**, 245-258.

Section 5.1

Christensen, J. H., and coauthors, 2007: Regional Climate Projections. *Climate Change 2007: The Physical Science Basis*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY. [Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Ch11.pdf].

Christensen, N., and D. P. Lettenmaier, 2006: A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. *Hydrol. Earth Syst. Sci. Discuss.*, **3**, 3727-3770.

Utah Division of Water Resources, 2007: Drought in Utah: Learning from the Past – Preparing for the Future. *Utah State Water Plan*, 124 pp. [Available at <http://www.water.utah.gov/DroughtReport/binder2A.pdf>].

Section 5.2

Lall, U., and M. Mann, 1995: The Great Salt Lake: A barometer of low-frequency climatic variability. *Water Resources Research*, **31**, 2503-2515.

Section 5.3

USDA, 2006: 2006 Annual Bulletin, p. 37. [Available at http://www.nass.usda.gov/Statistics_by_State/Utah/Publications/Annual_Statistical_Bulletin/Pdf/ab06/pg3706.pdf].

Utah Division of Water Resources, 2001: Utah's Water Resources: Planning for the Future, 73 pp. [Available at http://www.water.utah.gov/planning/SWP/SWP2001/SWP_pff.pdf].